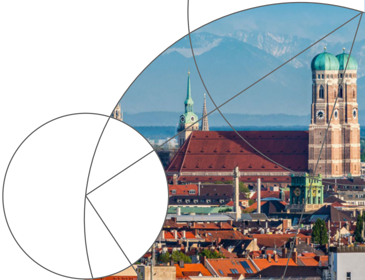
CLOCKWORKING FLAVOR

ALONSO, AC, DILLON, KAMENIK, MARTIN-CAMALICH, ZUPAN JHEP 1810 (2018) 099 [ARXIV:1807.09792]

ADRIAN CARMONA BERMUDEZ

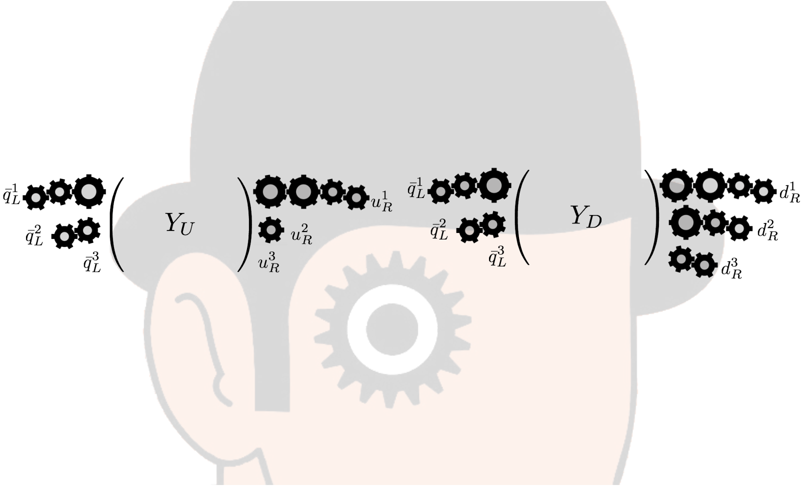
PRISMA+ CLUSTER OF EXCELLENCE & MAINZ INSTITUTE FOR THEORETICAL PHYSICS

MIAPP WORKSHOP: FLAVOR 2019: NEW PHYSICS IN FLAVOR FROM LHC TO BELLE II



May 21, 2019

A CLOCKWORK SOLUTION TO THE FLAVOR PUZZLE



THE CLOCKWORK MECHANISM

Generic mechanism to generate large hierarchies:

- in couplings Plot stolen from Kamenick's Planck 17

g  $g_{\text{eff}} = g \times q^{-N}$

$\frac{1}{q} \times \frac{1}{q} \times \ldots \times \frac{1}{q}$ N - times

[Choi,Kim,Yun, '14]

[Choi,Im, '15]

[Kaplan,Rattazzi, '15]

[Giudice,McCullough, '15]

...

- in scales

$$\Lambda_{\text{eff}} = M/g_{\text{eff}}$$

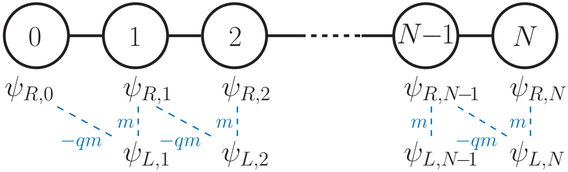
It is used to solve the hierarchy problem such

$$v_{\text{EW}} \sim M_{\text{Planck}} \times q^{-N}$$

In some cases, it can be viewed as the deconstructed version of the Linear Dilaton Model [Antoniadis, Arvanitaki, Dimopoulos, Giveon, '11][Baryakhtar, '12][Cox, Gherghetta, '12]

CLOCKWORKING A SINGLE FERMION

One chiral fermion $\psi_{R,0}$ plus N vector-like fermions ψ_k



$$\mathcal{L}_{\psi_R} = i\sum_{j=0}^{N} \bar{\psi}_{R,j} \not{D} \psi_{R,j} + i\sum_{j=1}^{N} \bar{\psi}_{L,j} \not{D} \psi_{L,j} - m\sum_{j=1}^{N} \left(\bar{\psi}_{L,j}\psi_{R,j} - q\bar{\psi}_{L,j}\psi_{R,j-1}\right) + \text{h.c.},$$

- We have $2N+1$ chiral symmetries broken by $2N$ mass parameters $(q, mq) \Rightarrow$ We end up with a masless chiral state

- We assume all sites to share the same gauge group, i.e., $\not{D}$ is not site dependent

CLOCKWORKING A SINGLE FERMION

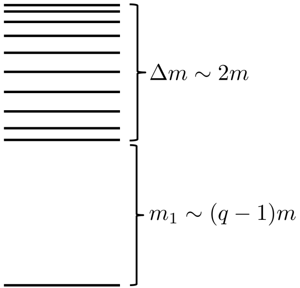
This pattern leads to a $N \times (N+1)$ mass matrix,

$$\mathcal{M}_\psi = m \begin{pmatrix} -q & 1 & 0 & \dots & 0 \\ 0 & -q & 1 & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & -q & 1 \end{pmatrix},$$

which leads, after diagonalization, to a mass spectrum

$$M_k^2 = m^2 \left(1 + q^2 - 2q \cos\left(\frac{k\pi}{N+1}\right)\right)$$

- Mass gap $M_1 \approx m(q-1)$
- Mass splitting $M_N - M_1 \approx 2m$

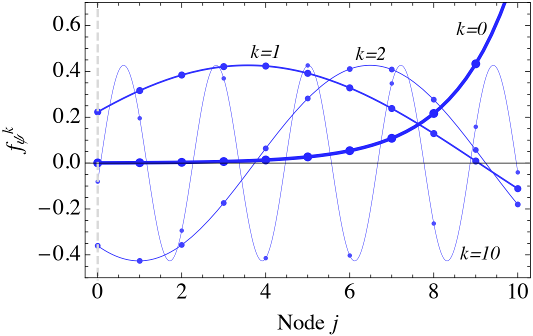


[Giudice,McCullough, '15]

CLOCKWORKING A SINGLE FERMION

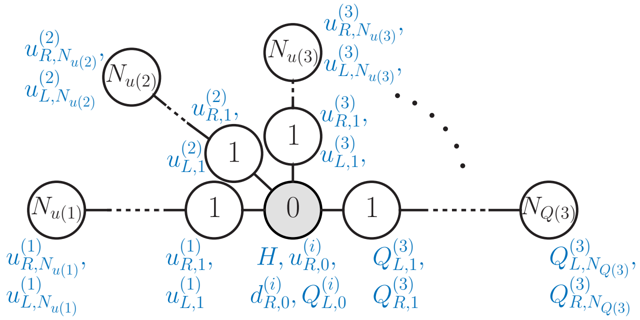
We are interested in the 0-site components f_ψ^k, i.e.,

$$\psi'_{R,k} = \sum_{j=0}^{N} V^R_{jk}\psi_{R,j}, \qquad f_\psi^k = V^R_{0k}, \qquad k = 0,\ldots,N,$$



$$f_\psi^0 = \begin{cases} \sim 1/q^N, & q \gg 1; \\ \frac{1}{\sqrt{1+N}}, & q \to 1. \end{cases}$$

CLOCKWORK FLAVOR



- One clockwork chain per SM chiral fermion (q_{ψ_i}, N_{ψ_i}), with the corresponding massless state identified with its SM counterpart
- The Higgs doublet lives in the 0-site

$$\bar{Q}_{L,0} Y_D H d_{R,0} + \bar{Q}_{L,0} Y_U \tilde{H} u_{R,0} + \text{h.c}$$

A CLOCKWORK MODEL OF FLAVOR

The SM-like Yukawas are given by

$$\left(Y_u^{\mathrm{SM}}\right)_{ij} = f_{Q(i)} \left(Y_U\right)_{ij} f_{u(j)} \sim q_{Q(i)}^{-N_{Q(i)}} \left(Y_U\right)_{ij} q_{u(j)}^{-N_{u(j)}}$$
$$\left(Y_d^{\mathrm{SM}}\right)_{ij} = f_{Q(i)} \left(Y_D\right)_{ij} f_{d(j)} \sim q_{Q(i)}^{-N_{Q(i)}} \left(Y_D\right)_{ij} q_{d(j)}^{-N_{d(j)}}$$

We can have hierarchical quark masses for $\mathcal{O}(1)$ proto-Yukawas if

$$q_{Q(1)}^{-N_{Q(1)}} \ll q_{Q(2)}^{-N_{Q(2)}} \ll q_{Q(3)}^{-N_{Q(3)}}$$
$$q_{u(1)}^{-N_{u(1)}} \ll q_{u(2)}^{-N_{u(2)}} \ll q_{u(3)}^{-N_{u(3)}}$$
$$q_{d(1)}^{-N_{d(1)}} \ll q_{d(2)}^{-N_{d(2)}} \ll q_{d(3)}^{-N_{d(3)}}$$

which leads to

$$\bar{m}_{u(i)} \sim v\, f_{Q(i)} f_{u(i)} \qquad \bar{m}_{d(i)} \sim v\, f_{Q(i)} f_{d(i)}$$
$$|L_{u,d}|_{ij} \sim f_{Q(i)}/f_{Q(j)} \quad |R_{u,d}|_{ij} \sim f_{u,d(i)}/f_{u,d(j)} \quad (\mathbf{V}_{\mathrm{CKM}})_{ij} \sim f_{Q(i)}/f_{Q(j)}$$

Two limits

There are two special limits

1. The universal q limit (or the FN limit)

$$q \sim 1/\lambda \gg 1 \quad \text{fixed and} \quad N_{Q(1)} \gg N_{Q(2)} \gg N_{Q(3)}, \;\; \ldots$$

- The total number of VLQs can be somehow reduced
- $q \sim 1/\lambda \gg 1 \Rightarrow M_k \sim qm$ Compressed spectra

2. The universal N limit (or the RS limit)

$$N \gg 1 \quad \text{fixed and} \quad q_{Q(1)} \gg q_{Q(2)} \gg q_{Q(3)}, \;\; \ldots$$

- A very large number of VLQs, $12 \times N$
- For the third generation $q \sim 1 \Rightarrow M_1 \approx m(q-1) \ll m$ Light gears

But we can find all kind of intermediate situations!

CW as the EFT of some new FN

- The CW models of flavor do not contain a dynamical flavon

- The differences between the universal-q CW and the FN models will depend on the values of $m_{\text{arg}\phi}$ and $m_{\text{rad}\phi}$

- The universal-q CW can be seen as the low energy effective theory – for some range of the parameter space – of a different realization of Froggatt-Nielsen where $U(1)_H$ is non-anomalous and

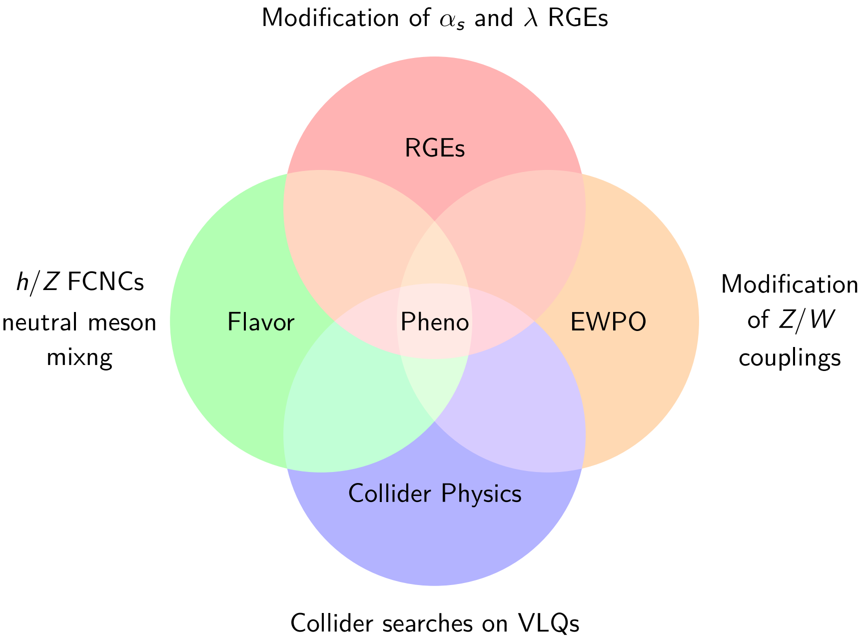
$$(Y_u^{\text{SM}})_{ij} \sim \left(\frac{\Lambda}{\langle \phi^* \rangle}\right)^{N_{Q(i)}+N_{u(j)}}$$

Clockworked FN

- If $U(1)_H$ is gauge, the new gauge boson have mass $m_H \sim g_H \langle \phi \rangle$ and mediate FNCNs $\Rightarrow$ m_H can be light enough if g_H is small [Zupan et al, soon]

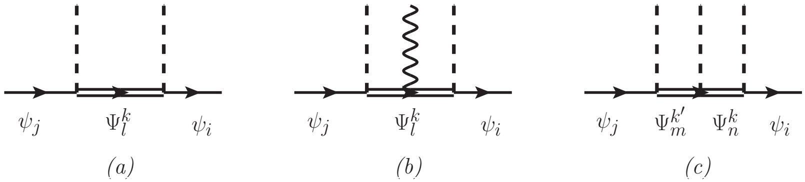
PHENOMENOLOGY

PHENOMENOLOGY



LOW ENERGY CONSTRAINTS

All these light gears will mess up with flavor data and EWPO; at $\mathcal{O}(\frac{v^2}{M^2})$



However, there is some Clockwork-GIM mechanism helping with FCNCs. For instance, $Zd_{L(i)}d_L(j)$ receives corrections

$$[\delta g_L]_{ij}^{Z_d} = \frac{v^2}{4} f_{Q(i)} f_{Q(j)} \left[Y_D M_d^{-2} Y_D^\dagger \right]_{ij}$$

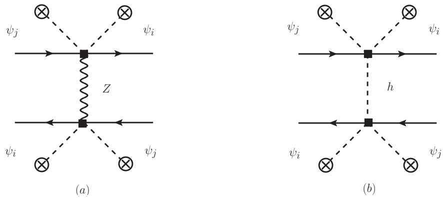
A strong constraint comes from $Z\bar{b}_L b_L$ since is not protected as $f_{Q(3)} = 1$

$$\Rightarrow M_{d(i)} \gtrsim 3.8 \text{ TeV}$$

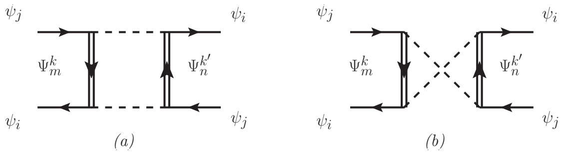
LOW ENERGY CONSTRAINTS

For neutral-meson mixing $K - \bar{K}, B - \bar{B}, D - \bar{D}, \ldots$ we have

- Tree-level $\mathcal{O}(v^4/M^4)$ contributions



- One loop $\mathcal{O}(v^2/M^2)$ terms (finite pieces and mixing terms)



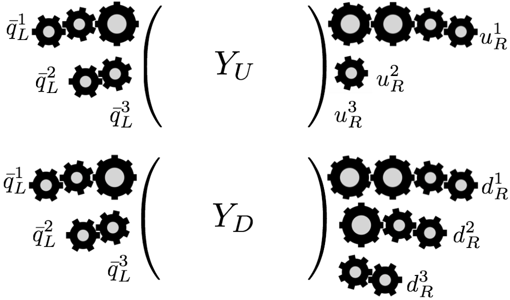
However, they still come with a large overlap supression!

LOW ENERGY CONSTRAINTS

Assuming $q \sim 1/\lambda$ and $N_{\psi(i)}$ such

$$F_Q = \text{diag}(\lambda^3,\ \lambda^2,\ 1), \quad F_u = \text{diag}(\lambda^4,\ \lambda,\ 1), \quad F_d = \text{diag}(\lambda^4,\ \lambda^3,\ \lambda^2),$$

we obtain



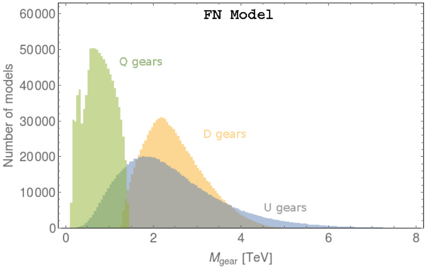
LOW ENERGY CONSTRAINTS

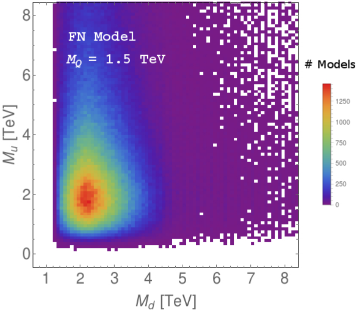
Assuming $q \sim 1/\lambda$ and $N_{\psi(i)}$ such

$$F_Q = \text{diag}(\lambda^3,\ \lambda^2,\ 1), \quad F_u = \text{diag}(\lambda^4,\ \lambda,\ 1), \quad F_d = \text{diag}(\lambda^4,\ \lambda^3,\ \lambda^2),$$

we obtain

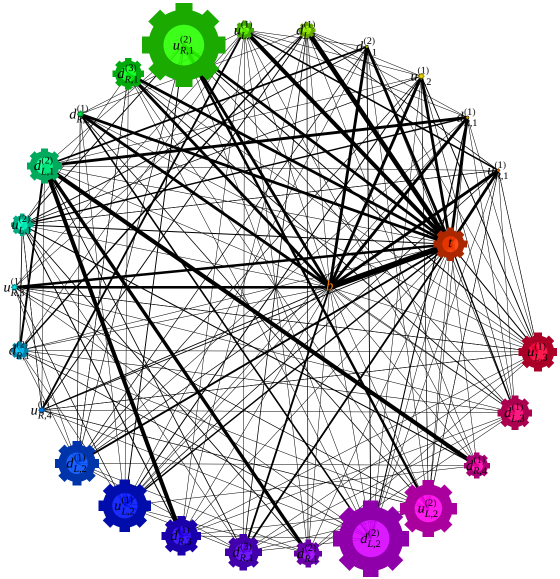
Process	U	D	Q	UQ	DQ
B_s-$\bar{B}_s$	λ^4, ¤*	λ^4, × and ¤	λ^7, ¤*	λ^7, ¤	λ^6, ×
B-$\bar{B}$	λ^6, ¤*	λ^6, × and ¤	λ^9, ¤*	λ^9, ¤	λ^8, ×
K-$\bar{K}$	λ^{10}, ¤*	λ^{10}, × and ¤	λ^{12}, ¤*†	λ^{12}, ¤†	λ^{12}, ×† and ¤†
D-$\bar{D}$	λ^{10}, × and ¤	λ^{10}, ¤	λ^{10}, × and ¤	λ^8, ×†	λ^{10}, ¤†





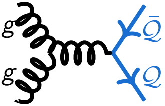
COLLIDER PHENO

Benchmark with $M_u \gtrsim 1.3$ TeV, $M_d \gtrsim 1.5$ TeV, $M_Q \gtrsim 1.7$ TeV

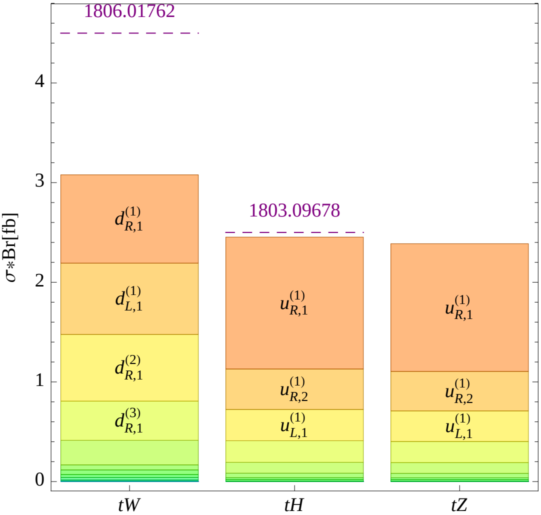


COLLIDER PHENO

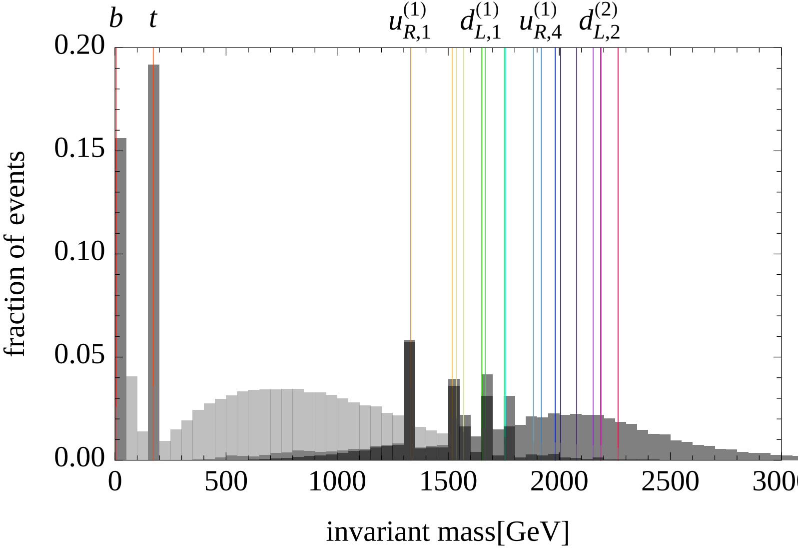
TOP PARTNER SEARCHES



$$pp \to \bar{\mathcal{Q}}\mathcal{Q} \to \bar{\mathcal{Q}} + tW/H/Z$$



HEMISPHERE CLUSTERING



Conclusions

- The CW mechanism can also provide a rationale for the flavor puzzle
- There are two interesting limits, corresponding to universal values of q or N, which point to rather different UV completions
- The universal-q limit can be most easily matched to a different limit of the usual FN models, which we called clockworked FN
- These models are embedded with some CW-GIM flavor protection that allows to have very light gears
- We have put forward new ways of looking for such a peculiar fermion spectrum at colliders

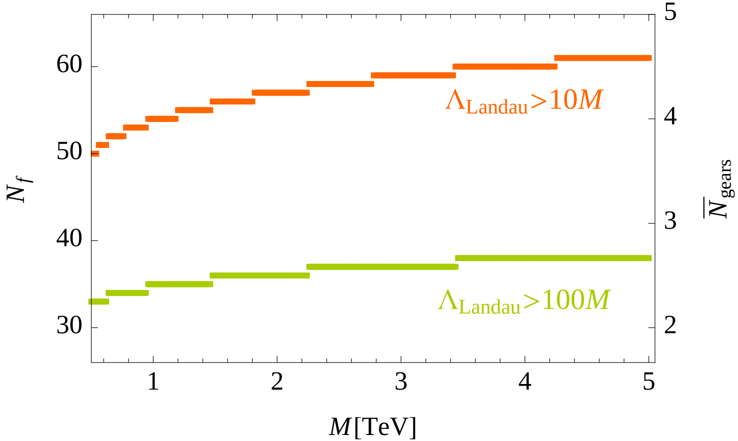
THANKS!

BACK - UP SLIDES

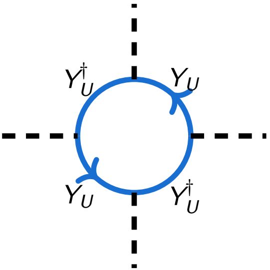
QCD LANDAU POLE

Having a bunch of heavy quarks will affect the running of α_s. Restricting ourselves to one loop,

$$\frac{d\alpha_s}{d\ln\mu} = -2\beta_0\frac{\alpha_s^2}{4\pi}, \quad \beta_0 = \frac{11N_c - 2N_f}{3},$$



HIGGS QUARTIC COUPLING



$$\beta_\lambda \supset 12\mathrm{Tr}\left(Y_U^\dagger Y_U\right)\lambda - 12\mathrm{Tr}(Y_U Y_U^\dagger Y_U Y_U^\dagger)$$

β_λ receives very large contributions from sizable Yukawas!

Therefore, we should have Yukawa entries a bit smaller than 1 to have

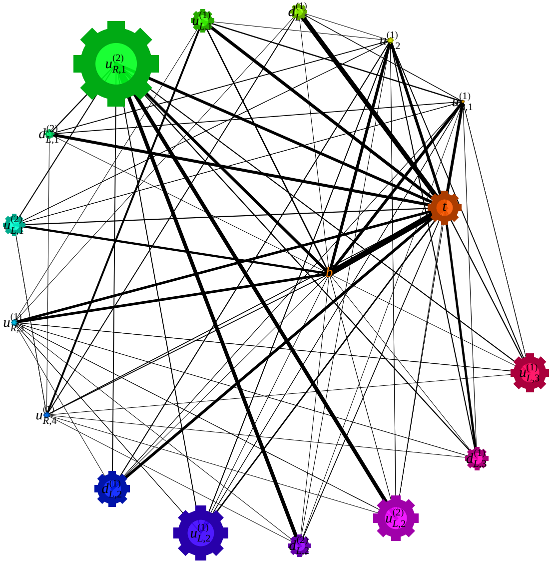
$$\mathrm{Tr}\left(Y_U^\dagger Y_U Y_U^\dagger Y_U\right) + \mathrm{Tr}\left(Y_D^\dagger Y_D Y_D^\dagger Y_D\right) \ll \frac{4\pi^2}{3}$$

This really disfavours the CW universal N limit since $y_t \sim (Y_U)_{33}/(1+N)$

However, one could add extra scalars or gauge bosons like e.g. [Sannino, Smirnov, Wang '19]

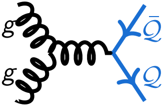
COLLIDER PHENO

Benchmark with $M_u \gtrsim 1.3$ TeV, $M_Q \gtrsim 1.7$ TeV, $M_d \gg M_{u,Q}$

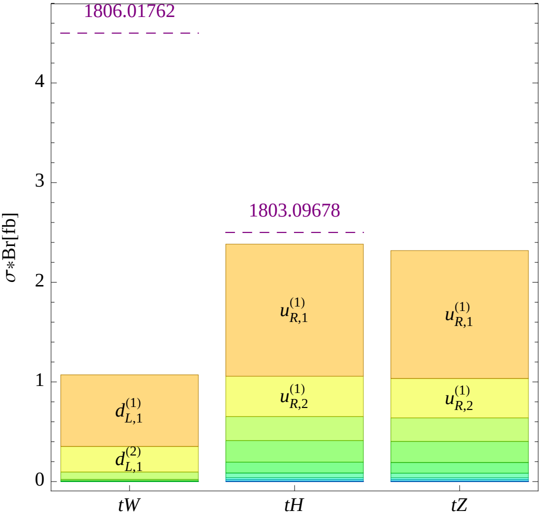


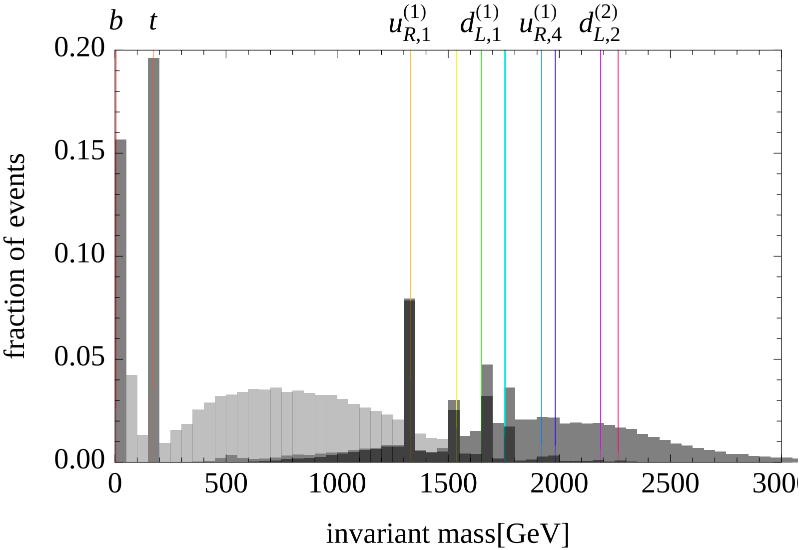
COLLIDER PHENO

TOP PARTNER SEARCHES



$$pp \to \bar{\mathcal{Q}}\mathcal{Q} \to \bar{\mathcal{Q}} + tW/H/Z$$




b
t
$u_{R,1}^{(1)}$
$d_{L,1}^{(1)}$
$u_{R,4}^{(1)}$
$d_{L,2}^{(2)}$
0.20
0.15
0.10
0.05
0.00
fraction of events
0
500
1000
1500
2000
2500
3000
invariant mass[GeV]